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1658 08/680681

002240.P002

PATENT

UNITED STATES PATENT APPLICATION

FOR

METHOD AND APPARATUS TO IMPROVE OVERALL PERFORMANCE OF A DGPS RECEIVER

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"Express Mail" mailing label number EM531308166US

Date of Deposit July 16, 1996

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METHOD AND APPARATUS TO IMPROVE OVERALL PERFORMANCE OF A DGPS RECEIVER

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

The present invention relates to navigation systems, and more particularly to an improved navigation and position method using Global Positioning System (GPS) receiver stations.

ART BACKGROUND

To assist sea, air, and land navigation and other purposes, the United State Government has placed a number of satellites in orbit around the earth in such a manner that, from any point on the earth, a user operating a roving receiver from an airplane or a ship may always have a line of sight on at least four satellites. This system is referred to as the Global Positioning System (GPS). A GPS receiver receives GPS data from the satellites; from the GPS data the roving receiver can determine its position. The GPS data includes data regarding the position of the satellite. However, the GPS data is corrupted by the U.S. Government in order to degrade the accuracy of calculations performed. Such errors are easily eliminated using the proper decoding algorithms and codes; however, such information is only available to the U.S. Military. Also, atmospheric and meteorological conditions, electromagnetic interference from terrestrial sources and other satellites, kinematic motion or orientation of the plane or ship the roving receiver is located on, and other uncertainties further degrade the signals.

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To ameliorate this problem, land-based reference stations at fixed, known locations have been erected to receive satellite transmissions and interpret the signals to generate measurement corrections, also referred to as DGPS (differential GPS) corrections. Using the true, known position of the receiver antenna at each reference station, these land-based reference stations derive measurement corrections that adjust the GPS data to produce more accurate results. These measurement corrections are transmitted, for example, via minimum shift keying (MSK) transmissions, to the roving receivers as deviations or offsets to be added to the measurements derived by the roving receiver from the GPS signals received directly from the satellites. An example of such a system is the Differential GPS NAVSTAR system operated by the U.S. Coast Guard to help ships navigate more accurately.

The use of reference stations has become so widespread, and the number of reference stations has grown so large, that it is quite likely that a receiver is in range of several reference stations at once. When this happens, very often the signal received from the reference station closest to the roving receiver is used to the exclusion of all others, since that signal, relative to those of the other reference stations, is usually the strongest signal and has the shortest signal path length. This method of operation reduces spatial decorrelation errors. The other measurement correction signals originating from other reference stations, although available to the roving receiver and containing measurement corrections, are generally ignored. This is justified by the fact that the likelihood of erroneous transmission increases with distance, and that the spatial decorrelation errors in the correction increase with distance.

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SUMMARY OF THE INVENTION

It is an object of the present invention to provide an improved method of navigation and apparatus using Global Positioning System (GPS) data and multiple sources of differential correction data.

In one embodiment, adjusted measurement corrections are used to "fill" gaps in unadjusted measurement corrections that are received from a preferred reference station. The gaps are caused by transmission link errors. A roving receiver performs a parity check on the data received from the preferred reference station to determine whether a transmission link error has occurred. Replacement corrections received from one or more alternate reference stations are adjusted for common mode differences which exist between the preferred station and the alternate stations.

In an alternate embodiment, the adjusted measurement correction is generated as a weighted average of the measurement corrections received from a plurality of reference stations.

In another embodiment, the common mode difference can be used to perform an integrity check on the data. For example, the detection of common mode difference values that vary significantly from prior recorded difference values can function as a flag to the receiver that errors exist. Also, measurement corrections received from the closest reference station can be compared to measurement corrections received from alternate reference stations to determine inconsistencies which affect the integrity of the data.

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BRIEF DESCRIPTION OF THE DRAWINGS

The objects, features and advantages of the present invention will be apparent from the following detailed description in which:

Figure 1 is an illustrative diagram of the differential GPS environment.

Figure 2a and Figure 2b are simplified flow charts illustrating embodiments of the method of the present invention.

Figure 3 illustrates wave forms received from a reference station.

Figure 4a and **Figure 4b** are simplified block diagrams that illustrate embodiments of receivers in accordance with the teachings of the present invention.

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DETAILED DESCRIPTION

The present invention organizes information from several reference stations that receive position information from the Global Positioning System (GPS) satellites, determines the magnitude of errors associated with the satellite transmissions, and re-transmits corrections to these errors to a roving receiver. The roving receiver uses the measurement corrections received from reference stations to adjust the pseudo range and pseudo range rate change measurements that the roving receiver takes from the received satellite signal. The corrected measurements are then used to produce an estimate of the roving receiver's position and velocity. When one or more reference stations are inoperative, however, the present invention organizes data from one or more functioning reference stations and forms adjusted measurement corrections at the roving receiver.

Alternately, because erroneous measurement corrections are potentially worse than the absence of measurement corrections , in an alternate embodiment, the present invention also checks the measurement corrections generated by reference stations to determine if the measurement corrections may be erroneous, and only uses measurement corrections that appear to be error free. Therefore, the system of the present invention corrects for the noise and other error sources carried by the satellite transmissions, and further compensates for the errors that occur during transmission of the measurement corrections from the reference stations to the roving receivers.

Although the methods and apparatus of the present invention are hereafter described with reference to GPS satellites, it will be appreciated that the teachings are equally applicable to positioning systems which utilize pseudolites or a combination of satellites and pseudolites. Pseudolites are

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ground based transmitters which broadcast a PRN code (similar to a GPS signal) modulated on an L-band carrier signal, generally synchronized with GPS time. Each transmitter may be assigned a unique PRN code so as to permit identification by a remote receiver. Pseudolites are useful in situations where GPS signals from an orbiting satellite might be unavailable, such as tunnels, mines, buildings or other enclosed areas. The term "satellite", as used herein, in intended to include pseudolite or equivalents of pseudolites, and the term GPS signals, as used herein, is intended to include GPS-like signals from pseudolites or equivalents of pseudolites.

It will be further appreciated that the methods and apparatus of the present invention are equally applicable for use with the GLONASS and other satellite-based positioning systems. The GLONASS system differs from the GPS system in that the emissions from different satellites are differentiated from one another by utilizing slightly different carrier frequencies, rather than utilizing different pseudorandom codes.

Referring to **Figure 1**, a number of satellites 102, 103 associated with the GPS encircling the earth transmit their positions in a broadcast mode to all points within their respective fields of view on the earth's surface. Land-based reference stations 104, 105, 106, 107 and roving receivers located on sea vessel 108 and aircraft 109 can determine their positions using the GPS data directly received from the satellites ("uncorrected GPS data"). Although examples of roving receivers are given as receivers located on or as part of moveable objects, the roving receiver can be part of a stationary object that receives both the uncorrected GPS data and measurement corrections. Furthermore, although the reference stations described herein are land-based, it is readily apparent that the reference stations are not limited as such

so long as the reference stations can generate and transmit the measurement corrections to the roving receiver.

Signals received directly from a satellite are corrupted by a number of error sources. These include the effects of Selective Availability (SA) that are deliberately introduced by the Department of Defense (DOD) to limit the accuracy of non-military receivers. Other direct signal errors include Ephemeris prediction errors in both satellite position and satellite time/frequency offsets and errors in the estimation of ionosphere and troposphere delay. To combat the effects of the errors, a reference station located in a known position develops a measurement correction for each satellite, which, when added to the uncorrected measurement obtained by the reference station, will result in the correct position being obtained. The measurement corrections are transmitted, for example, by MSK transmitters, and are received by MSK receivers at the roving receiver. The roving receivers use the measurement corrections to correct the uncorrected GPS data to generate more accurate position and navigation information.

The system of the present invention takes advantage of the fact that most roving receivers are within range of receiving signals containing measurement corrections from a plurality of reference stations. Although previously it has been assumed that the best results are achieved by using measurement corrections only from the reference station closest in physical distance to the roving receiver, the system of the present invention utilizes data from additional reference stations to minimize errors that may occur in the measurement corrections received from the closest reference station.

One embodiment of the process of the present invention is generally described with reference to **Figure 2a**. Referring to **Figure 2a**, at step 205, the roving receiver receives uncorrected GPS data. At step 210, measurement

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correction data streams are received from more than one reference station, for example, the two closest reference stations. As noted earlier, reception of measurement corrections from two reference stations is not problematic as most roving receivers are typically within range of multiple reference stations. Alternately, data from other reference stations (not necessarily the two closest) can be used.

An error detection process is performed on the measurement correction data streams received from the closest reference station, step 215. A variety of error detection processes are contemplated to detect errors caused by, for example, dropped bits in the data stream. In the present embodiment, checksums or parity determinations are computed and compared to the checksums or parity values transmitted in the measurement correction data stream. If the values do not match, a transmission error has occurred.

At step 220, if an error is found in the measurement correction data stream, the erroneous portion of the measurement correction data stream is replaced with data derived from a corresponding portion of a measurement correction data stream received from an alternate reference station such as the second closest reference station. It is acknowledged that measurement corrections received from the closest reference station provide the best measurement correction. Therefore, only the portion of the measurement correction data stream found to be defective is replaced with measurement correction data that is derived from the measurement correction data stream received from the alternate reference station.

The replacement data derived from the measurement correction data stream of the alternate reference station may be generated in a variety of ways. For example, the replacement data may simply be the corresponding

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measurement correction data received from the alternate reference station. Preferably, the data from the alternate reference station is adjusted to account for common mode difference that exists between signals received from different reference stations. Typically, this common mode difference is due to a time bias and frequency bias caused by the two reference stations using unsynchronized docks.

Referring to **Figure 3**, the drawing illustrates two wave forms 310, 320, representative of the measurement correction data streams for a single satellite received respectively from a first reference station which is closest to the roving receiver, and a second reference station, which is next closest to the roving receiver. Area 330 represents a portion of the first data stream in which transmission link errors occurred. As noted above, these errors can be detected using known techniques such as parity and checksum tests. Prior to the detection of transmission link errors (e.g., dropped bits), the roving receiver calculates a common mode difference 340 between the first and second wave forms 310, 320. Preferably, this is computed on a continuous or periodic basis to maintain current information.

As noted above, the common mode difference preferably includes the time bias and frequency bias that occurs between reference station clocks. Thus, in one embodiment, the common mode difference takes into the account the time bias that occurs due to the varying distances from the satellite, as uncorrected GPS data is used by the reference station to generate the measurement corrections. The time bias reflects the fact that the oscillators used by the reference stations are not phase locked. As can be seen by the similarity in wave forms in **Figure 3**, the correction code data received from both reference stations are approximately the same except for the time bias and the frequency bias. Thus, in an alternate embodiment, the

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common mode difference further takes into account the rate bias which occurs between reference stations. As before, the rate bias occurs as the reference station oscillators are not frequency locked.

Although the common mode difference due to the time bias and the frequency bias can be calculated prior to the detection of any errors and factored into the replacement data, it is preferred that all the measurement corrections received from the reference stations be continuously adjusted to eliminate for the time/frequency bias such that biases are adjusted to approximately zero. A variety of techniques can be applied to minimize the effect of the time and frequency biases. For example, a mean value of the pseudo range measurement corrections (PRC) received from each reference station can be determined and subtracted from each pseudo range measurement correction received to remove the time bias. Similarly, a mean value of the range rate corrections (RRC) received from a reference station can be compared and subtracted from each range rate correction.

Preferably, the process is performed for multiple groups of measurement corrections at a plurality of snapshots in time to produce a plurality of mean values. These mean values are filtered to produce a constant mean value that can be applied to subsequent measurement corrections received. This process relies in part on the observation that reference stations utilize extremely stable oscillators. Therefore, after a plurality of measurement corrections over a period of time are received, e.g., over a period of .10 - .90 seconds, the mean values can be combined in a variety of ways to produce a constant mean value. For example, one way is to average the mean values together.

A preferred technique to handle the common mode time and frequency bias difference between reference stations is to estimate the value

of the biases difference for each satellite's measurement correction. The most recent corrections are given the most weight and corrections whose age exceeds a predetermined threshold are not considered.

Consider the following general example where measurement corrections $PRC_{AN}(T_1)$, $RRC_{AN}(T_1)$ and $PRC_{BN}(T_2)$, $RRC_{BN}(T_2)$ and differential corrections for satellite N generated by reference stations A and B are valid at times T_1 and T_2, respectively. [$PRC_{AN}(T_1)$ is the pseudo range correction from reference station A for satellite N at time T_1; $RRC_{AN}(T_1)$ is the range rate correction from reference station A for satellite N at time T_1; $PRC_{BN}(T_2)$ is the pseudo range correction from reference station B for satellite N at time T_2; and $RRC_{BN}(T_2)$ is the range rate correction from reference station B for satellite N at time T_2.]

If the correction time delta (T_2-T_1) exceeds a base threshold, then the effects of SA acceleration are considered to be too large for a valid bias comparison to be made. Measurements indicate that SA acceleration rarely exceeds $0.01m/s^2$. Therefore, using a base threshold of 10 seconds would allow an SA contribution of only $0.5x0.001x10^2=0.5$ meters.

An estimate of the time bias difference between the reference stations is obtained by propagating the corrections from time T_1 to time T_2:

Time Bias Difference Estimate $(T_2) = PRC_{AN}(T_1) + (T_2-T_1) \times RRC_{AN}(T_1) - PRC_{BN}(T_2)$

Similarly, the frequency bias difference estimate is obtained by differencing the two range rate corrections:

Frequency Bias Difference Estimate $(T_2) = RRC_{AN}(T_1) - RRC_{BN}(T_2)$

The Time Bias Difference Estimate and Frequency Bias Difference Estimate are applied to Time Difference and Frequency Difference filters, respectively, using weights that are a function of the size of the time

difference. If the time difference is small, then the estimates are given a greater weight than if the time difference is large. This reduces the effect of SA acceleration on the filtered results.

The above process is repeated for all satellites and correction sets. The filtered outputs of Time Bias Difference and Frequency Bias Difference can then be used to modify corrections received from reference station A to appear as if they were received from reference station B, and vice-versa. The modified corrections from station A can then be used to fill in for corrections missing from station B.

In another embodiment, the modified corrections from station A and the unmodified corrections from station B can always be used in the roving receiver's determination of position and velocity. This has the added benefit of increasing the correction update rate and reducing overall latency, even in an error-free environment.

As noted earlier, the measurement correction received from one reference station, for example, the closest reference station, can be adjusted as needed to compensate for error using a corresponding portion of the measurement correction data received from alternate reference station(s). In an alternate embodiment, the measurement corrections received from a plurality of reference stations can be combined to produce a single measurement correction used by the roving receiver to correct the uncorrected GPS data. Referring to **Figure 2b**, at step 240, the uncorrected GPS data is received at the roving receiver. At step 250, the measurement corrections are received from a plurality of reference stations. The received measurement corrections are adjusted to minimize the time and frequency bias, step 260. At step 270, the measurement corrections are then combined to form a combined measurement correction that is used, along with the

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GPS data, to compute position information regarding the roving receiver, step 280. For example, one method to combine the measurement corrections is to use weighting functions to minimize the effects of errors in transmission of the measurement corrections received from different reference stations.

A variety of weighting functions and parameters are contemplated. For example a simple weighting function could be the summation of percent values of the data originating from a plurality of reference stations, the percent value corresponding to the distance of the transceiver from the receiver. More particularly, measurement corrections originating from the closest transceiver would be given greater weight than the data originating from other transceivers.

By continuously combining the measurement corrections, the need to detect errors is eliminated. Alternately, the combined measurement corrections is used only when an error in transmission from the first transceiver is detected to provide the corresponding replacement data for the erroneous portions or the entire measurement correction as discussed above. Measurement corrections obtained from multiple reference stations can be combined using a least squares technique to mitigate the errors associated with measurement correction latency and spatial decorrelation.

In addition, multiple reference stations can be used to perform integrity monitoring of the transmissions received from the reference station primarily providing the measurement corrections, such as the closest reference station. For example, the common mode difference among the reference stations can be monitored to detect when significant jumps in the common mode difference occurs. This indicative of error in the transmission originating from one of the reference stations. The roving

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receiver can respond to detection of jumps in the common mode difference measured a variety of ways. For example, the roving receiver may be programmed to drop the current transmission of measurement corrections received and wait for the next transmission. Alternately, the roving receiver may utilize measurement corrections received from an alternate reference station.

Simplified block diagrams of illustrative receivers are illustrated in **Figures 4a and 4b. Figure 4a** is illustrative of a differential GPS receiver 410 that utilizes measurement corrections in accordance with the teachings of the present invention. Preferably the receiver 410 includes a MSK receiver for receiving measurement corrections and operates in accordance with specifications set forth by the Radio Technical Commission For Maritime Services (RTCM) for Differential NAVSTAR GPS Service (RTCM Special Committee No. 104, P.O. Box 19087, Washington , D.C. 20036). However, it is contemplated that the invention is readily applicable to other types of receivers.

Other sources of differential GPS information transmitted over a variety of media can also be used. For example, differential measurement corrections can be received over FM subcarrier signals (such as radio and television broadcast channels), from satellites (whether geostationary or otherwise) or across media such as cable, telephone or cellular telephone connections. The advantage to some of the alternate media is a greater number of reference stations is accessible to the roving receiver. Although the roving receiver of the present embodiment is described as receiving a measurement corrections from a single type of reference station (e.g., MSK transmitting reference station), it is contemplated that the roving receiver is configured to receive measurement corrections from a variety of types of

reference stations that transmit across alternate media, such as the media described above. The media across which the measurement corrections are received can be selectable by the roving receiver. For example, based upon integrity or error checks, the receiver can be programmable to switch to the media providing the best measurement correction data. Alternately, the receiver can switchably receive measurement corrections from a variety of reference station sources and combine the measurement corrections after adjustment for common mode differences.

Referring to **Figure 4b**, the receiver 410 includes receivers 415, 420 combining circuit 415, error detection circuit 425, and position determining circuit 430. This configuration of circuitry is illustrative; other configurations are readily apparent.

The roving receiver 410 includes multiple receivers 415, 420 which are compatible with the transmissions by the reference stations. Although the receivers 415, 420 are depicted as two physically separate receivers, both receiving MSK signals, it is preferred that one set of receiver hardware is utilized and software/firmware is used to tune to adjust the hardware to individually receive each transmission from each reference station within reception range of the roving receiver 410.

The measurement corrections received from the reference stations by the receivers 415, 420 are input to combination circuit 425. For purposes of discussion, the combination circuit is shown herein in block diagram form; a variety of hardware/software/firmware can be used to implement the functionality described herein. Preferably, the combination circuitry adjusts each set of measurement corrections received from each reference station to minimize the time and frequency bias. In addition, depending upon the embodiment used, the combination circuit 425 also checks for data validity

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using RTCM parity error checks on the measurement correction data and measurement correction integrity (e.g., using the common mode difference). The combination circuit 425 further combines the measurement corrections adjusted to minimize the time and frequency bias to produce combined measurement corrections utilized by the GPS receiver circuitry 430 to calculate the position of the roving receiver.

As noted above, a variety of circuitry to implement the functionality described above can be used. Another example is illustrated by the block diagram of **Figure 4b**. In this embodiment, the receiver 460 includes a processor 465, that executes functions in accordance with code stored in a memory 470. The memory 470 is also available to store data used in the calculations. The processor can be a variety of types including those referred to as signal processors, general purpose processors, microcontrollers and the like. The GPS data and measurement correction data streams are received through input ports 475. The processor 465 performs the computations necessary to minimize the time and rate bias, detect errors, combine the measurement correction data streams and compute the position of the roving receiver. The receiver position is output through output port 480.

The invention has been described in conjunction with the preferred embodiment. It is evident that numerous alternatives, modifications, variations and uses will be apparent to those skilled in the art in light of the foregoing description.

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